Attitude Control Approach for Solar Cruiser, a Large, Deep Space Solar Sail Mission

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Solar Cruiser
Class D Technology Demonstration Mission

Mission
Solar Cruiser will mature solar sail propulsion technology to enable near-term, compelling space missions for Heliophysics, NASA, and the nation.

Mission Technology Goals
Demonstrate solar sail propulsion technology to enable near- and mid-term Heliophysics science missions up to and including high solar inclination orbits, sub-L1 halo orbits, non-Keplerian solar and other planetary orbits

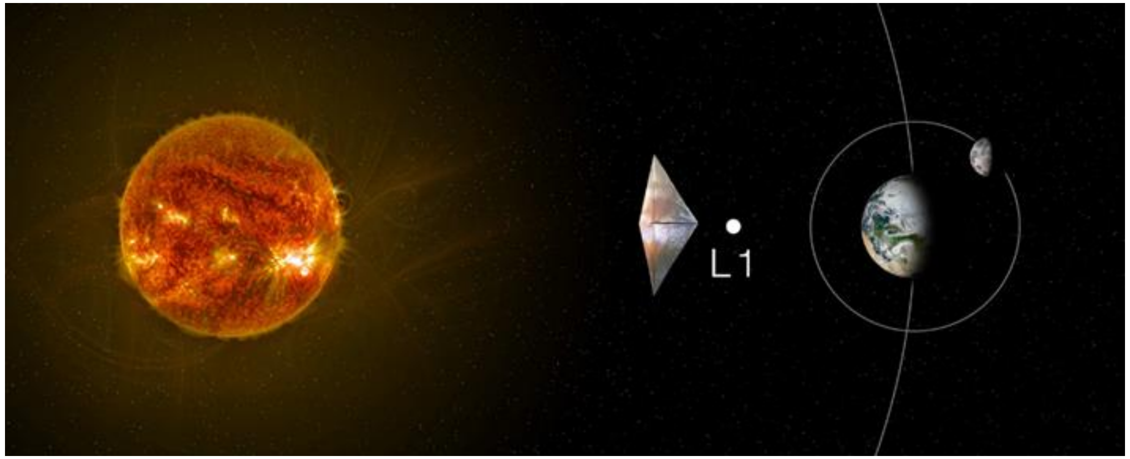
- Solar sail operation
- Scalability of sail technologies

The Team
NASA MSFC: PM/DPM/SE/MA, Solar Sail ADCS Software, MDNav, Mission Operations

Ball Aerospace: Sailcraft Bus (procured from BCT), Sailcraft I&T

Redwire: Composite Booms, Deployer, Active Mass Translator
NeXolve (Redwire Subcontractor): Sail Fabrication

Purdue & Univ. Alabama: Student Collaborations



Technical Details

Solar Sail
- Deployed Area: 1653 m^2
- Fabric: 2.5 micron thick Colorless Polyimide-1
- Composite Boom Lengths (X4): 29.5 m each

Momentum Management
- Reaction Wheels
- Active Mass Translation (AMT)
- IFM thrusters

Destination
- Sail-enabled, non-Keplerian sub-L1 halo orbit

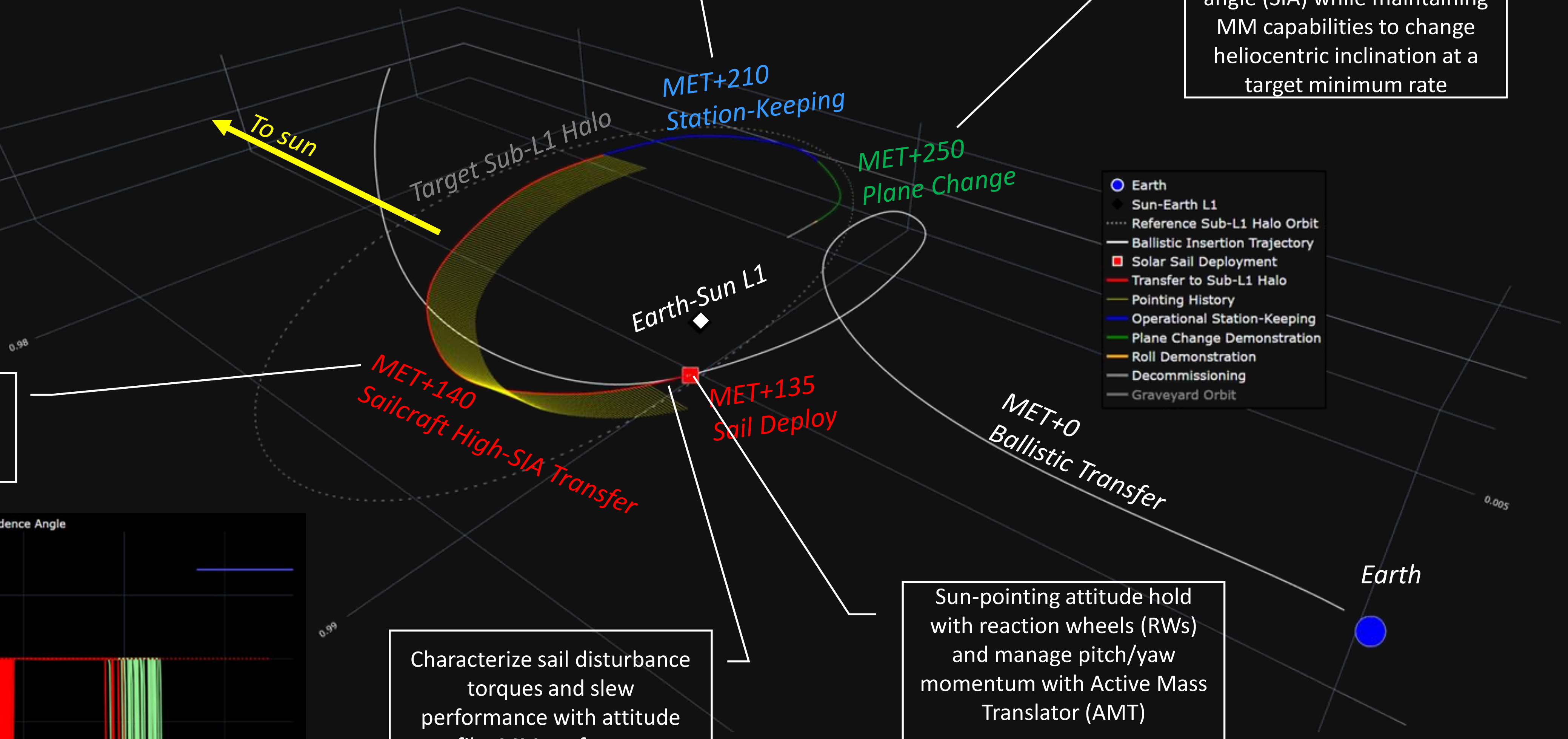
Credit: Les Johnson

The Solar Cruiser Mission

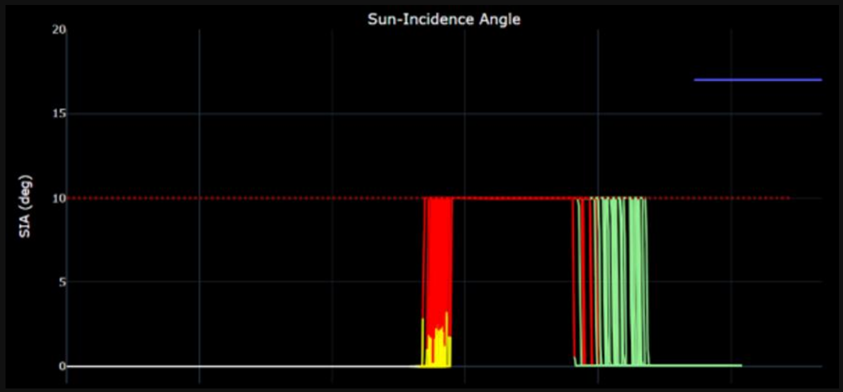
Total Mission Elapsed Time: ~11 months

Follow uplinked attitude commands while managing momentum

Acquire and hold maximum achievable sun incidence angle (SIA) while maintaining MM capabilities to change heliocentric inclination at a target minimum rate



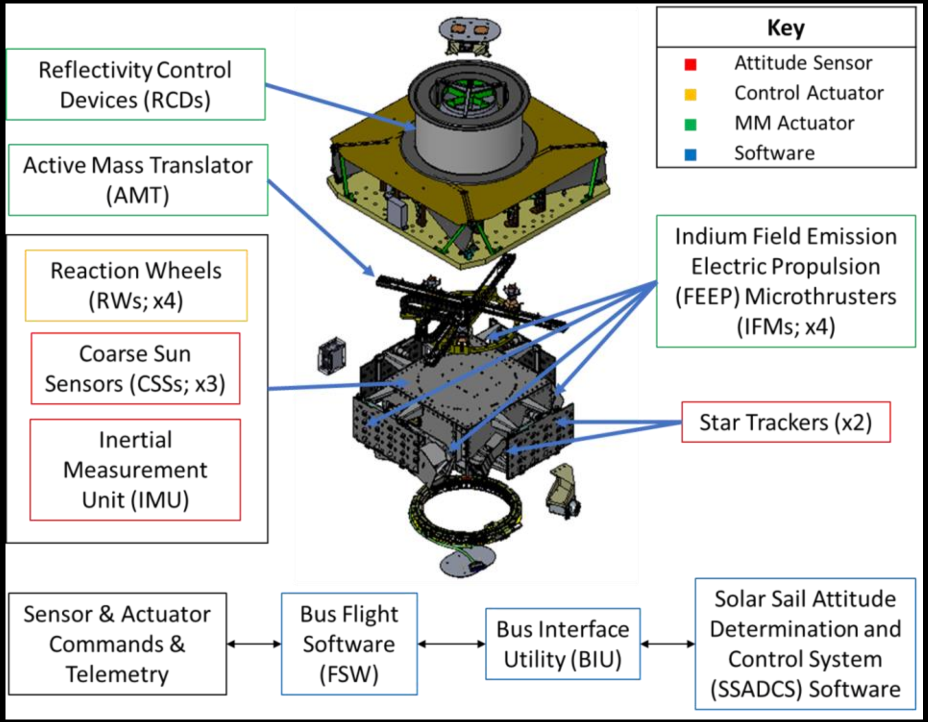
Follow uplinked attitude commands while managing momentum



Characterize sail disturbance torques and slew performance with attitude profile, MM performance, and pointing performance

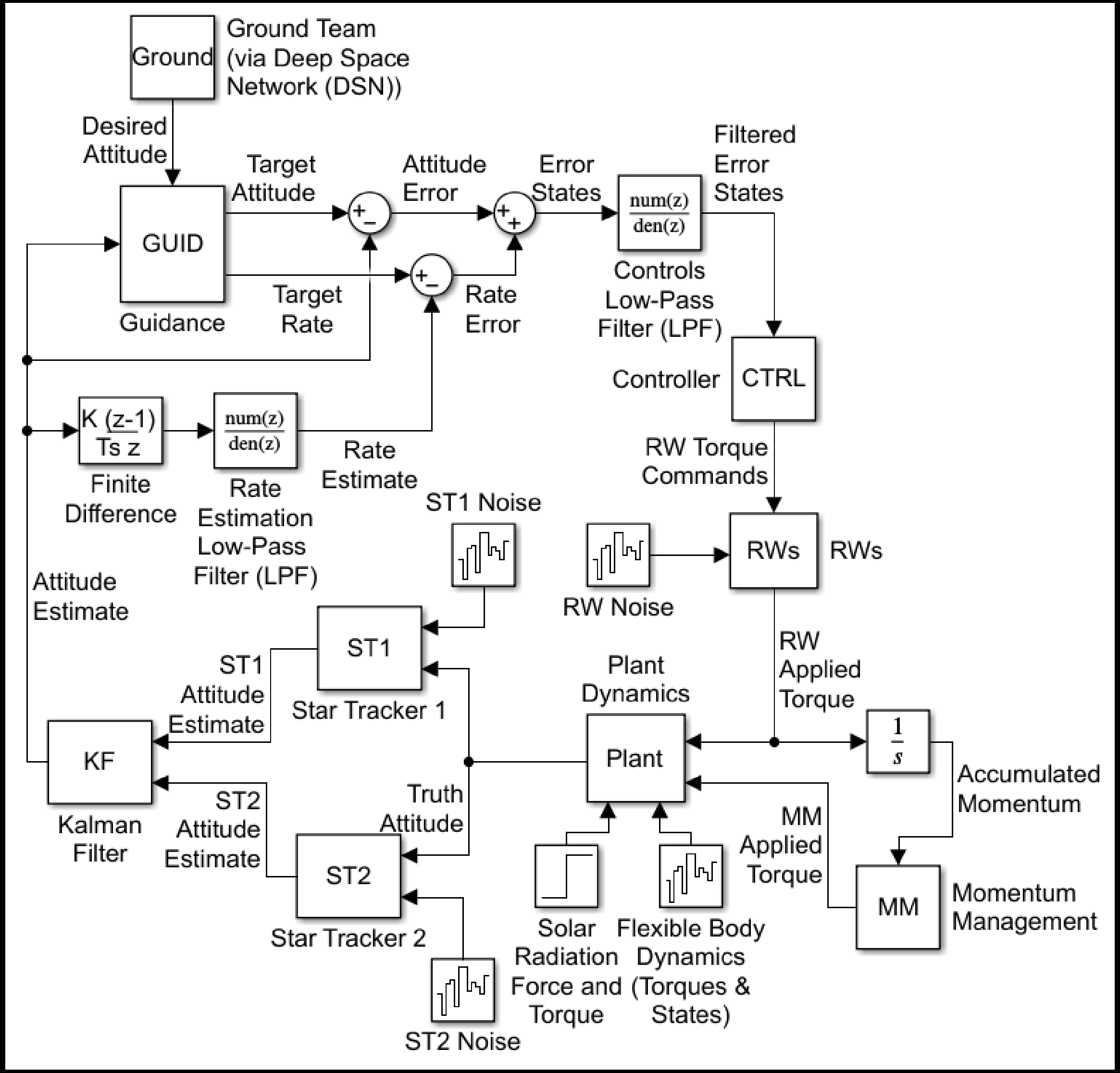
Sun-pointing attitude hold with reaction wheels (RWs) and manage pitch/yaw momentum with Active Mass Translator (AMT)

Architecture & Functions



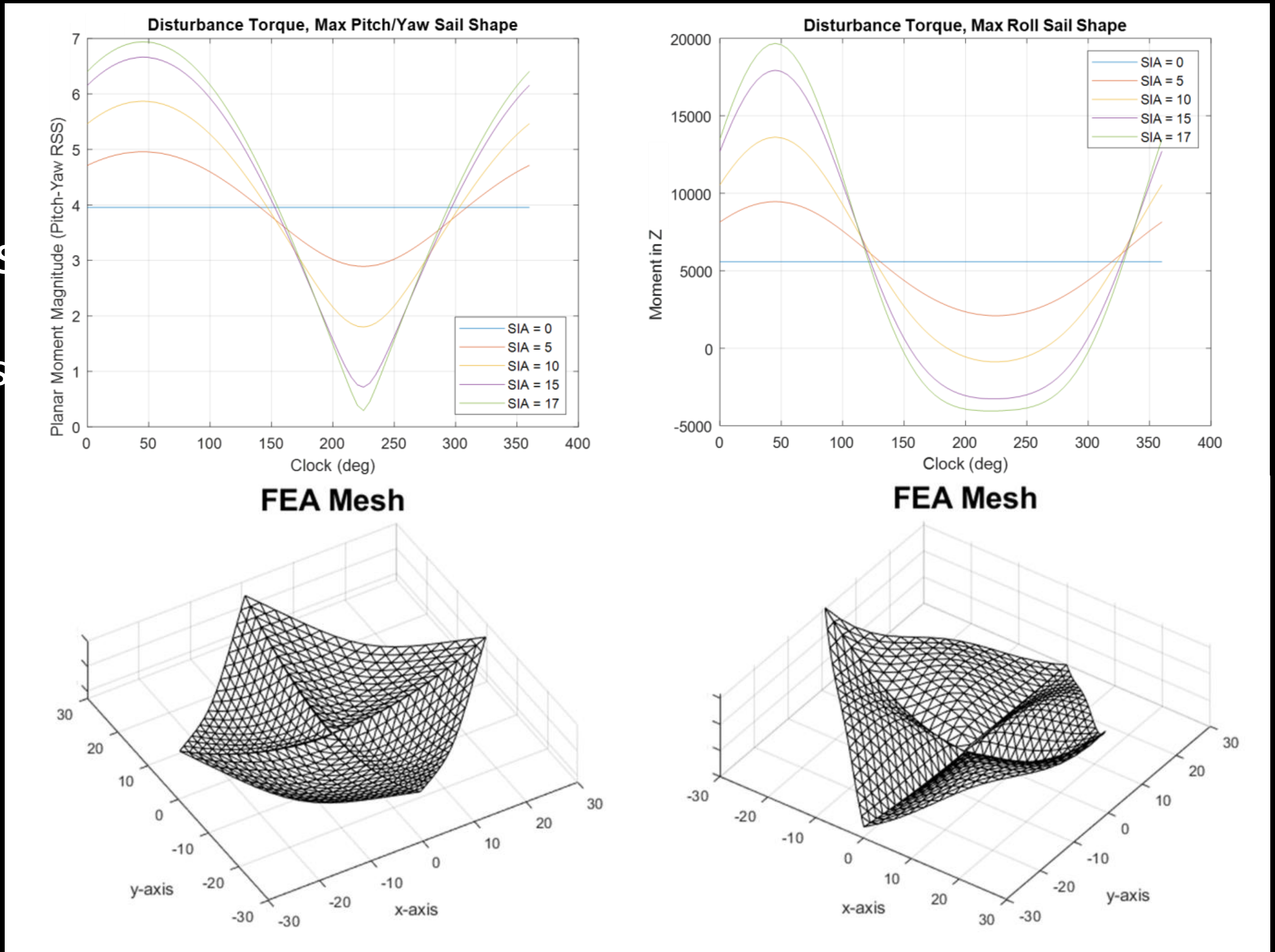
The SSADCS software controls the sailcraft attitude in flight by taking inputs from the bus attitude determination system and outputting commands to actuators used to maintain pointing control and manage momentum.

SSADCS Software Design



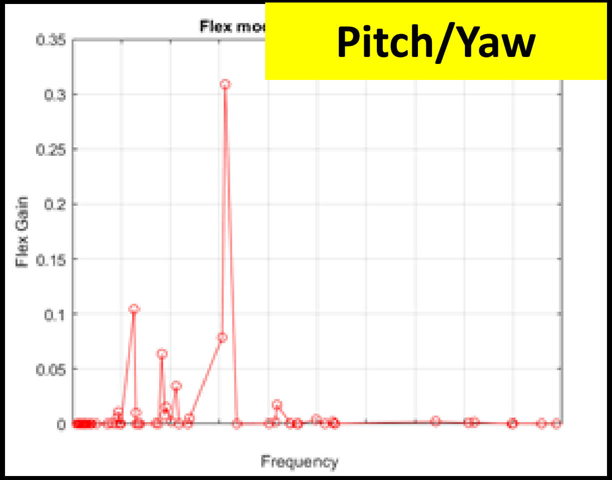
Sail Modeling

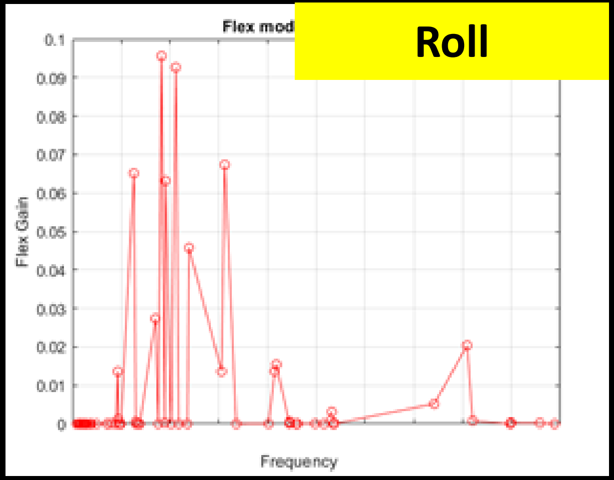
- **Critical for modeling disturbances and sizing actuators accordingly**
- Disturbance torques bounded using worst-case shapes from parametric sweep over the following parameters
  - Out-of-plane membrane deflection
  - Out-of-plane boom tip deflection errors
  - In-plane center of mass offset from geometric center
- Nominal out-of-plane boom tip deflection magnitudes due (mostly) to thermal effects are a major driver of disturbance torques (primarily pitch/yaw)
- Worst-case torques occur at highest SIA of 17 deg

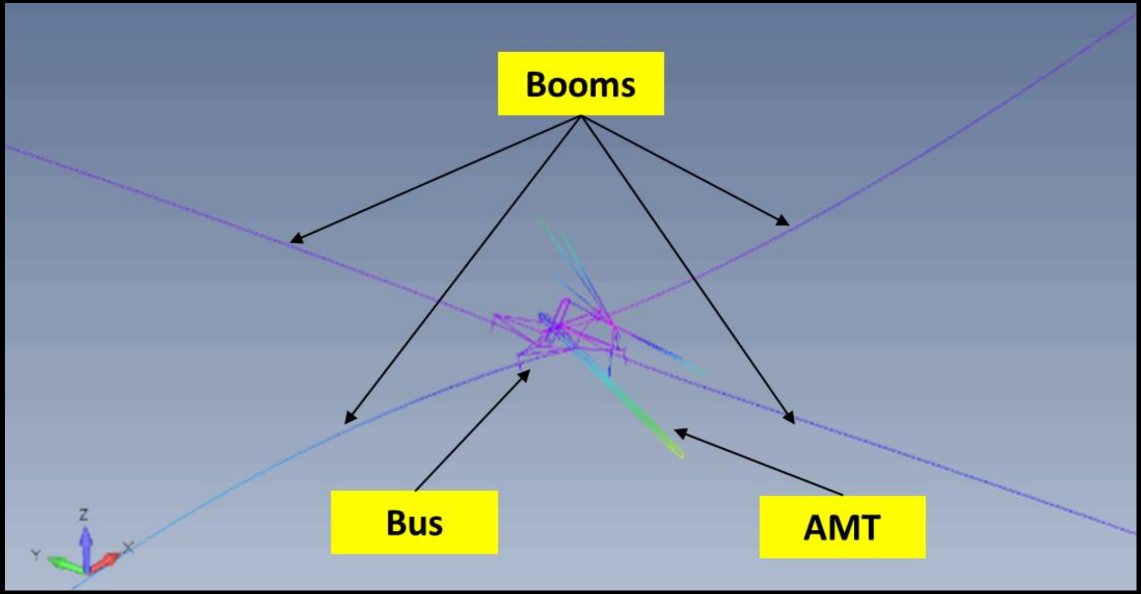


Flex and Control-Structure Interaction

- Mass-normalized, free-free normal modes generated from FEM with flexible sail membrane, booms, and AMT modeled
- Interaction between flex modes and bus where attitude sensors and control actuators are located is of particular interest
- Low-pass filter design:
  - Order: 2nd (20 dB/decade attenuation)
  - Cutoff frequency: 0.02 Hz



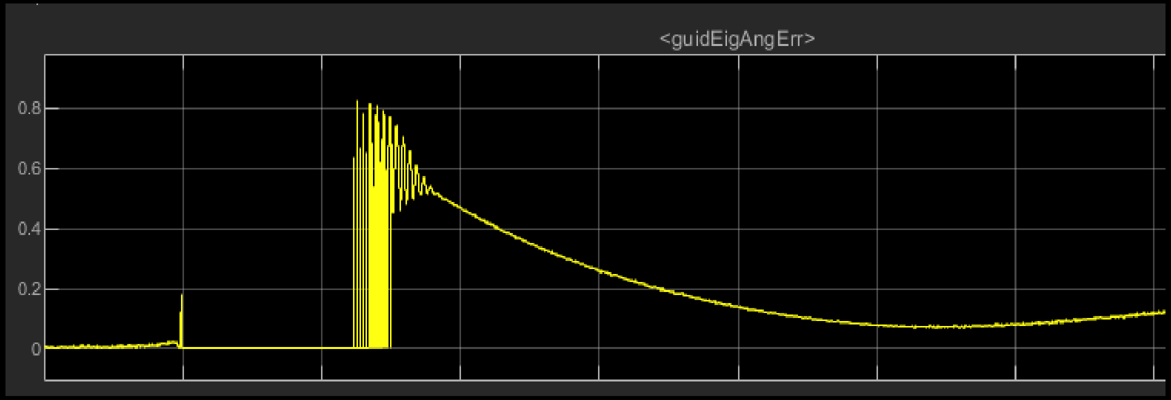




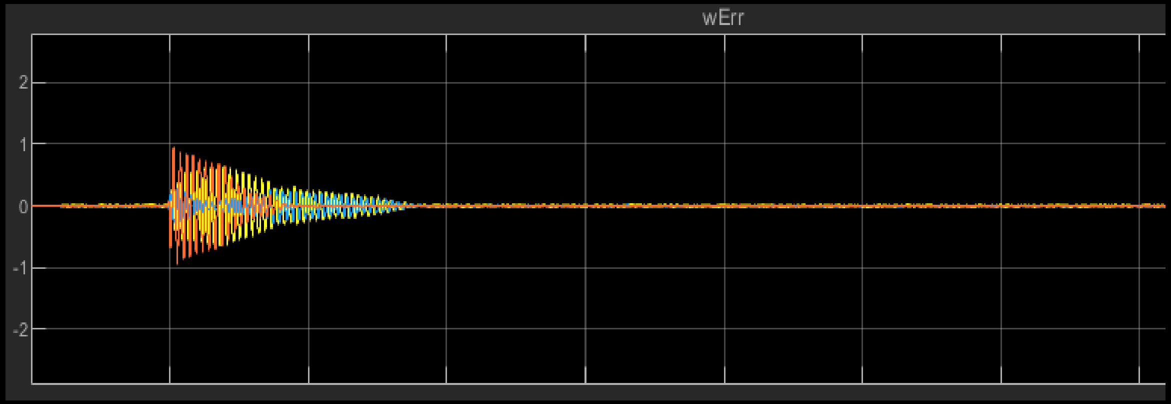
Sail Deployment

- **Key challenge: maintain 3 axis stability and control (within 5 deg SIA), and manage momentum, with rapidly and widely varying inertial properties (~3 orders of magnitude MOI over as little as ~45 minutes), as well as fairly indeterministic and potentially large disturbance torques**
- Current approach: Tune PID gains at intervals of 10% deployment progress and interpolate gains and principal axis transformation DCMs based on % deployed telemetry; enable AMT for torque trimming and desaturation

Attitude Error [deg]

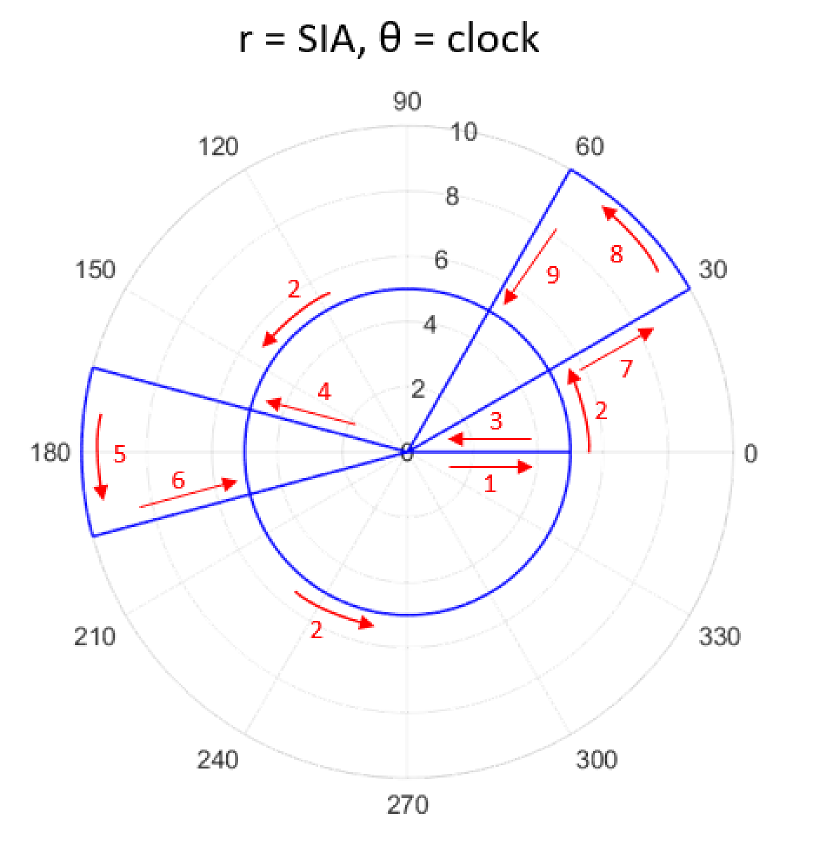


Attitude Rate [deg/sec]



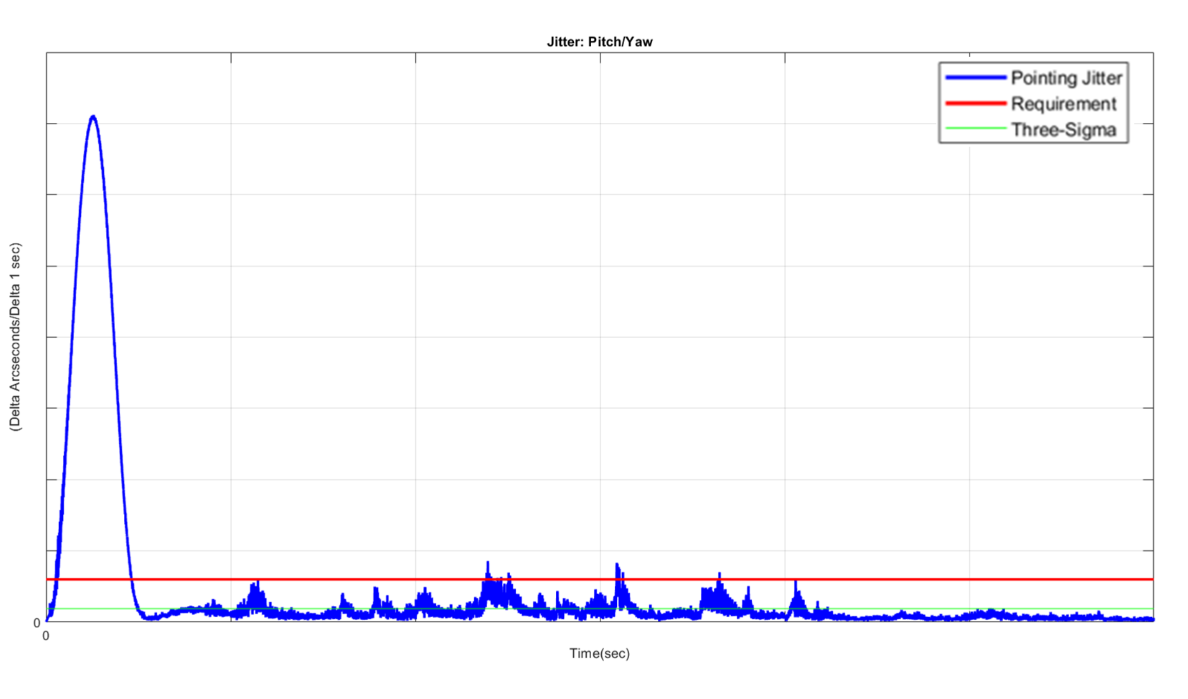
Sail Characterization

- Choreographed attitude profile to characterize disturbance torques vs. attitude (SIA and clock angle)
- Can be used for identifying ideal clock angle for commanding to reduce disturbances and/or validating the sail shape & torque models
- Timeboxed checkout activity driving slew rate requirement
- Required average slew rates over one slew to complete characterization in 4.5 days:
  - ≥ 0.002 deg/sec pitch/yaw
  - ≥ 0.001 deg/sec roll
- Slew performance limited by flex both directly (mitigating excessive modal excitations) and indirectly (low-pass filter limits responsiveness of control system to slew commands)



Pointing Performance Analysis

- Tracked as 3 Level 1 Requirements and TPMs: Pointing Accuracy, Pointing Stability, and Jitter
- Traces to capability of solar sails to serve as stable pointing platforms for science observations
    - Requirements/TPM thresholds derived from Heliophysics science instrument needs (e.g., coronagraph)
- Control error and rate of convergence of pointing stability and jitter driven by sail disturbance torques and flex and the control system response to these things
- Residual pointing stability and jitter response dominated by interaction of noise due to RW imbalance and flex modes



Momentum Management Analysis

- MM control authority (average control torque over average disturbance torque over course of one MM de/activation cycle; equivalent to inverse of duty cycle) tracked as TPM
- Level 1 requirement specifies design SIA (10 deg; 17 deg at L2 with embedded margin), which is a primary driver for required MM capabilities
- **Key challenge: balance needs of MM with power, thermal, and lifetime constraints of actuators**
  - Key metrics: duty cycle (% on time), thermal cycle (frequency of hot/cold cycles), activation frequency (motor start/stop cycles)
  - E.g., operating temperature constraints required significantly faster thruster de/activation cycles, putting tight requirements on MM thresholds